

EFFECTS OF LOCOMOTION OVER VARIED TERRAIN ON SOLDIER VIGILANCE

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ABSTRACT

Walking is generally viewed as an automatized skill, requiring little ongoing attentional control in neurologically intact adults. However, a growing body of research demonstrates that attention is required when moving over difficult terrain. This has particular ramifications for warfighters, who must often move over challenging terrain while remaining vigilant to threats in their environment. The present study extends the basic research in this area by considering adaptation in attention allocation as warfighters gain familiarity with particular terrain. Soldier volunteers walked for 30 minutes on a treadmill while performing an attention-demanding secondary task. Eye-tracking was used to monitor gaze behavior and “terrain” complexity was varied by having participants step over markings placed at irregular intervals on the treadmill belt. Secondary task response times improved over the 30 minute period in the marking-present condition, indicating adaptation of attentional control. Additionally, volunteers consistently made fewer and shorter fixations on the treadmill belt relative to the secondary task stimuli. These results are discussed relative to challenges dismounted warfighters face in maintaining situation awareness during movement over rugged terrain.

1. INTRODUCTION

Anyone who has observed a toddler for any period of time can appreciate the remarkable complexity of bipedal locomotion and the degree to which it can consume attentional resources. Novice walkers frequently lose balance and fall when distracted by interesting objects and events. Similarly, anyone who has witnessed a co-worker or loved one tripping and falling, or personally experienced such an accident, understands that walking requires some measure of attention even in adults. However, walking is generally taken for granted as a highly skilled, automatized behavior (e.g., Paul, Ada, and Canning 2005) despite both anecdotal evidence and empirical data suggesting that attention plays a critical role in adapting gait to dynamic environments.

Over the past several years a number of studies have examined the role of attention during locomotion, most often with regard to elderly and neurological populations

– groups that suffer debilitating falls at a greater rate than younger, neurologically intact people. A common method in these studies is to pair a walking task with an attention-demanding secondary task and observe changes in secondary task performance as a function of varying population variables or conditions on the primary walking task. The logic behind this “dual task methodology” is that variations in secondary task performance associated with manipulations of the walking task provide quantitative measures of how much attention is allocated to walking. Reduced secondary task performance under more demanding locomotion conditions suggests a greater allocation of attention to walking; conversely, increased secondary task performance would indicate that less attention was allocated to control walking.

Studies utilizing dual-task methodology have enumerated several critical factors influencing how attention is allocated to support gait and posture. For instance, the attentional demands of walking appear to fluctuate throughout the gait cycle, with increased demand during the single-support phase relative to the double-support phase (Lajoie, Teasdale, Bard, and Fleury 1996). This makes sense given that one leg must support the body while the swinging leg generates torques that must be counteracted by postural muscles to maintain balance. Data have also shown that the need for attention during the execution of gait and posture tasks increases with age (Brown, McKenzie, and Doan 2005; Kim and Brunt 2007; Melzer, Benjuya, and Kaplanski 2001; Sparrow, Bradshaw, Lamoreaux, and Tirosh 2002) and with neurological and neuropathic disorders that affect stability (Dingwell and Cavanagh 2001; Haggard, Cockburn, Cock, Fordham, and Wade 2000; Yardley, Gardner, Bronstein, Davies, Buckwell, and Luxon 2001). Intriguingly, the nature of the secondary task used to probe attention control does not seem to matter. Studies have found effects of gait and postural manipulations on a variety of tasks including simple reaction time (Lajoie, Teasdale, Bard, and Fleury 1993), the Stroop interference task (Grabiner and Troy 2005; Weerdesteijn, Schillings, Van Galen, and Duysens 2003), and a relatively complex episodic memory task (Li, Lindenberger, Freund, and Baltes 2001; Lindenberger, Marsiske, and Baltes 2000). Of course, the common denominator across all of these secondary tasks is that they require a certain degree of attention for proper performance. However, the functional role of attention varies quite a bit between a simple

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reaction time task, which primarily depends on maintaining vigilance and orientation to a single target stimulus, and the Stroop task, which is characterized by involvement of attention networks related to inhibitory control.

The present study aims to extend current understanding of the role attention plays in controlling walking by addressing two questions. The first is whether the allocation of attention to walking versus a secondary task changes as individuals gain experience walking over a given type of terrain. Existing studies of attentional control during walking have used relatively short bouts of performance. However, given the flexibility of the perceptual-motor system in adapting to novel circumstances, for example, force fields (Lackner and Dizio 2005), delayed visual feedback during manual tracking (Foulkes and Miall 2000), and the adoption of unusual locomotion regimes (Sparrow and Newell 1994) it seems plausible that the demand for attention during walking might gradually decline as individuals gain experience with movement over particular terrain. To explore this issue we tracked changes in attentional strategies over the course of 30-minute bouts of walking.

The second question addressed in the present study concerns the spatial and temporal dynamics of attention allocation during walking. Previous studies in this area have largely focused on changes in the amount of attention allocated to walking as a function of various intra- and extra-personal factors. Under capacity theories of attention (e.g., Wickens 1980), declines in secondary task performance as walking-related variables change suggest that more attention is being allocated to walking. Structural bottleneck theories (Pashler 1999) offer a broadly similar view on declines in secondary task performance under more challenging walking regimes, positing that dual-task interference patterns result from constraints on sharing critical computational mechanisms. Both accounts, and assorted hybrid models, address internal processes guiding the shifting of limited attentional resources among competing tasks. A complete understanding of attention control during walking requires additional analyses of where attention is being deployed and the timing of shifts in attention amongst various objects in the environment.

How can one assess the spatial allocation of attention during walking? Attention researchers have developed a sophisticated array of experimental procedures for accessing fine-grained spatiotemporal properties of attention, such as spatial cueing (Eriksen and Hoffman 1972; Posner and Cohen 1984). Unfortunately, most standard methods are unsuitable for studying allocation of attention during walking as they require research participants to remain seated before a computer. The present study aims to circumvent this limitation by using

eye-tracking as an index of where attention is deployed during walking. Though gaze direction and the locus of spatial attention can be disassociated (Hunt and Kingstone 2003) they are generally coupled under normal behavioral conditions (Land and Lee 1994). When behaving “in the wild”, people generally look where they attend. By using an eye-tracker designed for data collection with ambulatory subjects, it should be possible to quantify where attention is deployed when walking is paired with an attention-demanding secondary task.

2. METHOD

2.1 Participants

Twelve male Soldiers assigned to the Human Research Volunteer detachment at the U. S. Army Natick Soldier Research, Development, and Engineering Center participated in this study as part of their normal duties. Volunteers ranged in age from 18 to 24 years ($M = 20.38$, $SE = 0.8$), were right-handed, and had normal or corrected to normal vision and hearing. All participants volunteered to take part in the study and were treated in accordance with the ethical principles of the American Psychological Association.

2.2 Procedure

Volunteers completed two test sessions, held on separate days. During each session they walked for two 30 minute blocks at their own pace on a modified Woodway Force 1.0 treadmill fitted with a 3 m long by 0.57 m wide belt. We manipulated the complexity of “terrain” by requiring volunteers to step over markings on the treadmill belt. In the “marking-present” condition 0.5 meter-wide strips of red electrical tape were placed on the belt at random intervals between 0.46 and 1.84 m to simulate terrain obstacles. Volunteers were instructed to step over these markings and an experimenter monitored their performance, triggering a buzzer each time they stepped on a marking. In the “marking-absent” condition nothing was placed on the belt and volunteers were free to adopt their natural gait. In both conditions volunteers were instructed to walk as fast as possible and walking speed was recorded throughout.

While walking volunteers performed a vigilance task involving monitoring a row of nine bicolor LEDs located above the front edge of the treadmill belt, approximately 3 m away from the participants. In separate 30-minute blocks the LEDs were placed either approximately at eye-level (1.7 m above the treadmill belt) or at ground-level (even with the surface of the treadmill belt). At random intervals between 10 and 30 seconds one of the nine LEDs turned red or green. Volunteers had 3 seconds to indicate the color of the LED by pressing one of two

buttons mounted on the treadmill handrail. The order of target positions and colors was randomized for each of the two blocks performed during the test sessions. Each participant completed a total of 90 trials in each block of the vigilance task, with 5 trials of each target color at each of the nine LED positions. Volunteers were instructed to correctly identify as many targets as possible without reducing walking speed or stepping on any markings. The order of marking presence/absence and LED placement were counterbalanced across volunteers.

A custom-built eye-tracker (ISCAN, Woburn, MA) was used to measure gaze. This system included a lightweight visor mounted to a kevlar helmet equipped with an infrared camera for recording corneal reflection and pupil location of the left eye, along with a regular video camera for recording the scene within participants' field of view. The gaze direction computed from the corneal reflection and pupil location was corrected for head position using a magnetic head-tracker. Analysis software computed points of intersection between gaze direction and a pair of pre-defined planes encompassing the treadmill belt and the vigilance task targets. The sampling frequency of the system was 60 Hz and its approximate accuracy was $\pm 1^\circ$ of visual angle.

Before the first test session volunteers completed a training session in which they practiced the walking and vigilance tasks both separately and in combination. At the end of this session a Qualisys ProReflex motion capture system was used to record gait kinematics in the marking-present and marking-absent conditions to quantify the impact of that manipulation on walking performance. Volunteers walked for five minutes in each condition at a natural pace. Motion data were captured during the final 30 seconds of this period, yielding approximately 10 complete gait cycles worth of kinematics.

3. RESULTS

3.1 Manipulation Check

To verify that the marking manipulation induced changes in gait, left shank kinematics were used to compute the mean and standard deviation of stride length. Paired samples t-tests were used to compare these measures across the marking-present and marking-absent conditions. Mean stride length did not change, $t(11) = -0.71$, $p = .49$, $d = -0.25$, with stride length in the marking-absent condition ($M = 1.37$ m, $SE = .05$) statistically identical to stride length in the marking-present condition ($M = 1.33$ m, $SE = .03$). In contrast, analysis of the standard deviations of stride length showed that stride length variability was significantly greater when markings were placed on the treadmill belt ($M = 10.20$ cm, $SE = 1.57$) than when they were not ($M = 4.40$ cm, $SE = .64$), $t(11) = 3.79$, $p < .01$, $d = 1.39$. These findings

demonstrate that our manipulation of "terrain" did indeed produce changes in gait.

3.2 Primary Walking Task Performance

To assess the impact of terrain variability on performance of the primary walking task analyses were run on the number of markings participants stepped on during the marking-present test blocks as a function of vigilance target position and time and on mean walking speed as a function of marking presence/absence, time, and vigilance target position. Analysis of stepping errors did not reveal any significant changes in error rates across time or vigilance target position. On average, participants committed very few stepping errors during the 30-minute test blocks ($M = 2.38$, $SE = .49$). Indeed, given mean walking speed (reported below) and the spacing of the markings on the treadmill belt one can estimate that the proportion of stepping errors relative to the total number of markings participants encountered during the test blocks was only 0.11%.

To further assess performance on the primary walking task an analysis was conducted on mean walking speed. The only significant effect was the difference in speed between the two target positions, $F(1, 11) = 5.25$, $p < .05$, $\eta_p^2 = .32$. Participants walked faster when the targets were placed at eye level ($M = 1.09$ m/s, $SE = .05$) relative to when the targets were placed at ground level ($M = 1.03$ m/s, $SE = .05$). The stability in walking speed across marking condition and time together with the very low rate of stepping errors suggests that participants heeded instructions to emphasize walking performance over vigilance performance.

3.3 Secondary Vigilance Task Performance

Log-transformed mean response times on the vigilance task declined over time, $F(2, 22) = 3.86$, $p < .05$, $\eta_p^2 = .26$. The reduction in RT over time was almost perfectly linear, with an average reduction of 72 ms ($SE = 29.59$) from bins 1 through 3. More critically, the effect of time on RT also interacted with the presence of markings on the treadmill belt, $F(2, 22) = 3.59$, $p < .05$, $\eta_p^2 = .25$. The pattern of RTs, shown in Figure 1, demonstrates that the reduction of RT over time was confined to the marking-present condition and that no signs of improved performance occurred in the marking-absent condition.

Accuracy data were arcsine-transformed prior to analysis following recommended procedures for correcting the non-homogeneity of variance typical of proportion data (Neter, Kutner, Nachtsheim, and Wasserman 1996). Analysis of this data revealed that accuracy improved slightly over time, $F(2, 22) = 4.81$, $p < .05$, $\eta_p^2 = .30$, increasing by 6.8% from early to late phases. However, post-hoc comparisons using Tukey's

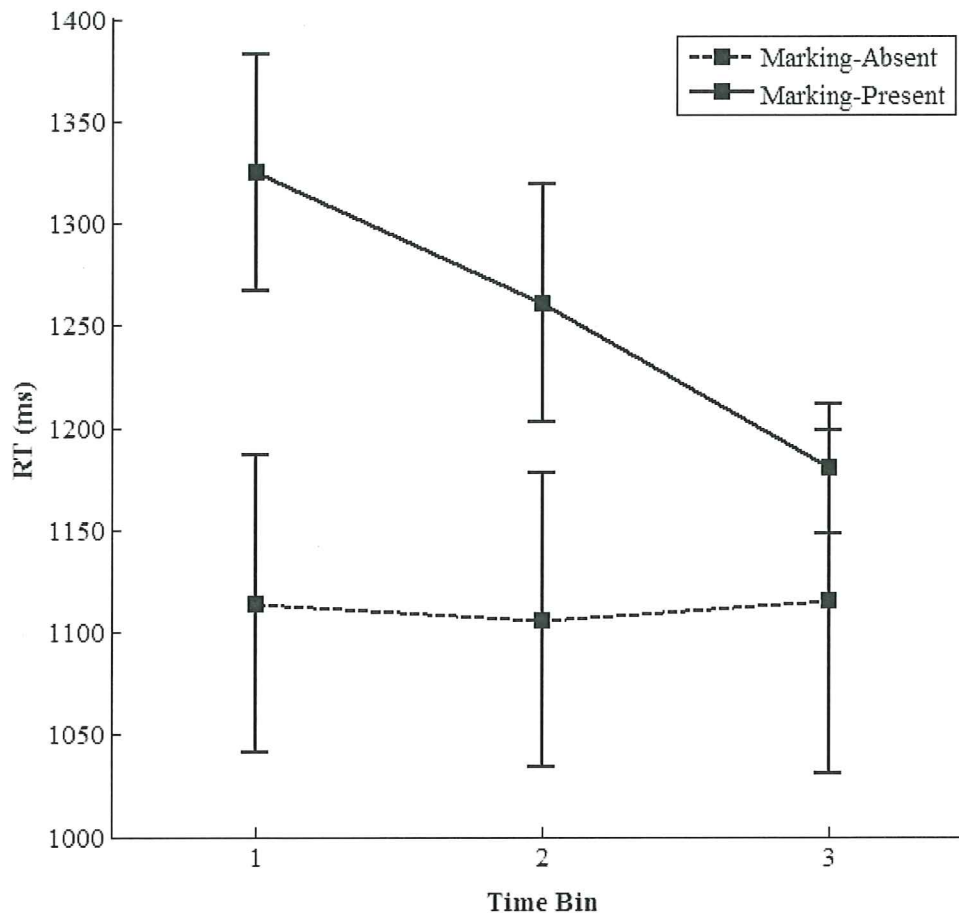


Figure 1. Mean vigilance task response time as a function of marking presence/absence and time. Error bars represent one standard error above and below the mean.

procedure revealed no significant differences between time bins, suggesting that the significant main effect of time on accuracy may be a statistical artifact driven by relatively low mean squared error. In addition, unlike RT, there was no significant interaction between marking presence/absence and time, $F(2, 22) = 2.21$, $p = .13$, $\eta_p^2 = .17$, observed power = .40. None of the other main effects or interactions for RT or accuracy was significant.

3.4 Eye-Tracking Measures

Eye-tracking data were processed to extract the proportion of overall fixations falling on the treadmill belt as a function of marking presence/absence, target position, and time. An analysis of the arcsine-transformed belt fixations revealed a significant main effect of marking, $F(1, 11) = 30.07$, $p < .001$, $\eta_p^2 = .73$. Participants almost never fixated on the treadmill belt in the marking-absent condition (proportional $M = .04$, $SE = .01$), but directed approximately one-third of their total

fixations to the belt in the marking-present condition ($M = .30$, $SE = .05$). None of the other main effects or interactions was significant, indicating that target position and time had limited effects on how participants chose to direct their gaze.

A separate analysis was run on the duration of fixations, calculated separately for those falling on the plane containing the vigilance targets and the plane of the treadmill belt. P-P plots of these data revealed strong skew, which was corrected by taking a natural log transformation of the raw data. For simplicity of exposition, however, the direction and magnitude of any significant ANOVAs will be reported in terms of mean fixation times. The log-transformed data were analyzed using a four-way repeated measures ANOVA with plane (belt versus target), marking presence/absence, target position, and time as factors. Fixations on the vigilance targets were an order of magnitude longer than fixations on the treadmill belt, with a mean of 1565 ms ($SE = 479$)

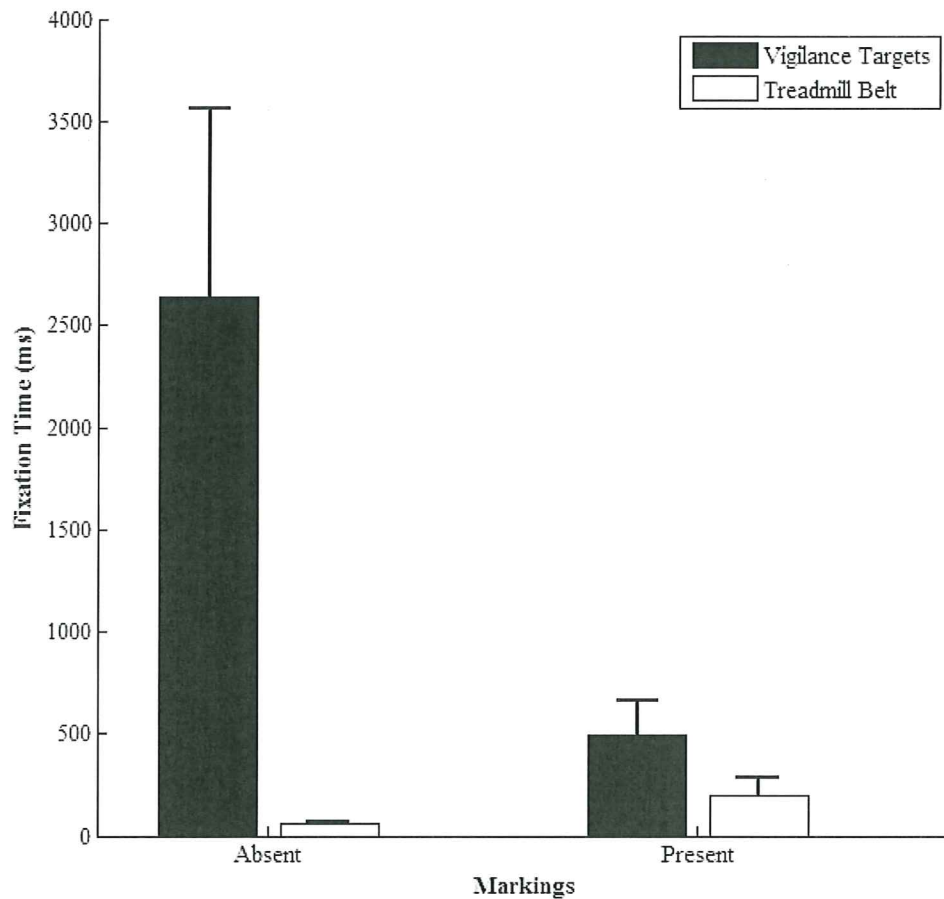


Figure 2. Mean eye fixation time as a function of marking presence/absence and plane (treadmill belt versus vigilance targets). Error bars represent one standard error above the mean.

versus 127 ms ($SE = 44$), respectively, $F(1, 11) = 76.96$, $p < .001$, $\eta_p^2 = .88$.

The interaction between plane and marking presence/absence was also significant, $F(1, 11) = 15.85$, $p < .01$, $\eta_p^2 = .59$. As presented in Figure 2, participants spent the vast majority of their time fixating on the vigilance targets in the marking-absent condition, making only very brief saccades on the treadmill belt. In contrast, in the marking-present condition fixations on the targets were much shorter and fixations on the treadmill belt were almost four times longer. The only other significant effect was the three-way interaction between plane, marking presence/absence, and target position, $F(1, 11) = 6.72$, $p < .05$, $\eta_p^2 = .38$. The primary driver of this interaction was a 153 ms decrease in the duration of fixations on the vigilance targets for ground-level versus eye-level positions in the marking-absent condition. Apart from this difference fixations were largely stable in

duration apart from the aforementioned interaction between plane and marking presence/absence.

4. DISCUSSION

The aims of the present study were to evaluate adaptation of attention control strategies during extended bouts of walking over terrain of varying complexity and to characterize the spatiotemporal properties of these strategies. Several interesting findings emerged. Analysis of vigilance response time and accuracy revealed evidence of adaptation in the strategic division of attention among the primary walking task and secondary vigilance task. Response times declined over time in the marking present condition, but not in the marking absent condition. This interaction is important because it suggests that performance improvements in RT over time were not simply the result of a general practice effect. In that case one would expect to see reductions in RT in both

walking conditions. Instead, the pattern of RTs observed here suggests that individuals became more efficient at shifting their allocation of attention between walking and the vigilance task when presented with the more complicated walking task. The lack of any statistically significant changes in accuracy over time bolsters the view that the changes in RT observed in the marking-present condition reflect a fundamental adaptation in attention control over time. Recall that, although vigilance accuracy was associated with a significant *F*-test with respect to temporal bin, post-hoc testing failed to show any real shifts in accuracy.

Whereas the vigilance task data showed that the allocation of attention between walking and a secondary task can adapt over time, the eye-tracking data reported above showed no evidence of changes over time in the spatiotemporal properties of visual attention. In the marking absent condition participants made very short and infrequent fixations on the treadmill belt relative to the vigilance targets. In essence, the strategy in this case could be characterized as sampling the ground plane just often enough to check footing and ensure that the body remained adequately centered on the treadmill. In contrast, fixations on the belt were much more frequent and of longer duration in the marking present condition, reflecting a need for additional visual information and attention to avoid stepping on the markings. Still, even in this case participants directed only around one-third of their total fixations at the treadmill belt. The strategy in this case appeared to involve taking longer and more frequent samples of the ground plane while reserving the majority of fixations for the vigilance targets.

The stability in these distinct spatiotemporal strategies – short infrequent sampling in the absence of obstacles versus longer and somewhat more frequent sampling when obstacles are present – suggests one of three possibilities. These strategies might reflect an optimal division of attention across time and space, perhaps resulting from years of experience in managing attentional load during locomotion. Alternatively, these strategies might reflect local minima in the space of possible attentional control strategies that were merely satisfactory for performing these tasks. Finally, it might be that adaptation in the spatiotemporal division of attention requires longer periods of performance than the 30 minutes used in the present study. Each of these alternatives offers interesting practical implications. For example, if the present spatiotemporal control of visual attention reflects a local minimum in the space of possible, acceptable strategies, then people might be induced to employ different and possibly better strategies by presenting cues in the environment (e.g., cues that attract attention to the ground).

One possible criticism of the current study is that we used a visual secondary task that promoted structural interference rather than capacity interference (Pashler 1999). We acknowledge that the inability to look in all directions at once may have contributed to declines in vigilance performance when the targets were placed at eye-level. However, similar performance decrements were observed when the targets were at ground level and it was possible for participants to view both the targets and treadmill belt simultaneously. Therefore, though structural interference may have played a role, it seems clear that the present data did indeed reflect capacity (or bottleneck) constraints on attentional control.

Furthermore, one might argue that instances of structural interference in which the need for vision to guide walking conflicts with the need for vision to detect other critical events in the environment are more common in the course of everyday behavior. Using an example of great importance to the present subject population, Soldiers are frequently required to walk over very challenging terrain (e.g., the foothills of Afghanistan) while remaining alert for threats from snipers, ambush, and improvised explosive devices. The present data suggest that walking over complex terrain can lead to significant reductions in “situation awareness” – a catch-all term used within the military community to refer to a Soldier’s perception of events unfolding within his or her environment and the ability to properly understand and react to those events. Lapses in awareness on the battlefield carry dire risks. Indeed, publicly available U.S. Defense Department statistics show that approximately 43.56% of American casualties in Iraq resulted from detonation of improvised explosive devices that went undetected. Similarly, an additional 12.2% of U.S. casualties were the result of sniper attacks, ambushes, and other forms of hostile action that are especially effective against distracted personnel.

The present study suggests an essential lesson for designers of equipment and training programs supporting dismounted infantry: Estimates of mental workload and available cognitive capacity must take locomotion into account. For example, infantry platoon leaders are frequently required to monitor two or more communications links while moving over difficult battlefield terrain. The present data suggest that the ability to quickly and accurately extract critical information from such multi-channel feeds will degrade when moving over rugged terrain. To prevent dangerous reductions in situation awareness, communications devices might be improved through adaptive technologies that restrict information flow based on terrain, movement speed, and other related factors. An alternative mitigation strategy would be to share communications-monitoring tasks more widely within the platoon during movement over rough terrain. This could be handled by automation or through

better training and operational procedures. As an additional and timely example, the present data suggest that warfighters may be less able to detect threats from ambush, snipers, and IEDs when moving on foot. To the best of our knowledge, the cognitive ramifications of controlling locomotion over complex terrain are not an explicit factor in current logistical and mission planning processes. However, casualties might be reduced if units moving over particularly difficult terrain (mountains, dense urban environments, etc.) were given priority in the assignment of unmanned aerial vehicles and scout/reconnaissance aircraft.

Returning to theoretical issues, another important question that must be addressed is the temporal dynamics of attention allocation during walking. In most settings, the complexity of walking changes as one proceeds along a chosen path. Periods of relatively simple locomotion control will be punctuated by postural challenges in the form of obstacles to be stepped over or circumvented, stairs to be climbed, and so on. So the need for attention during walking is likely to change, ramping up as one approaches an obstacle and receding after the obstacle is past. The dynamics of attention during walking could be mapped by pairing a walking task that includes a variety of challenging features with a continuous secondary task, such as manual tracking.

In addition, it would be valuable to apply theoretical concepts of attention to better understand the role played by various attention networks during walking. According to one influential view attention can be parsed into three neurocognitive networks dedicated to alerting, orienting, and executive control (Posner and Peterson 1990). Alerting involves sustaining attention over time (i.e., vigilance), orienting involves selecting task-critical information from ongoing and rich sensory data, and executive control involves resolving conflict among competing responses to selected sensory information. Lesion and imaging data demonstrate that these functional aspects of attention map onto neuroanatomical networks in frontal and parietal brain regions. The vigilance task used in the present study clearly loads heavily onto the alerting component of visual attention, with relatively smaller demands placed on orienting (stimulus location was unpredictable) and executive control (stimuli were presented in isolation, without conflict). Therefore the present study suggests that simultaneous performance of walking and an attention-demanding secondary task impacts the alerting component of attention. Additional research should explore how walking affects orienting and executive control. One straightforward approach would be to pair the present walking procedure with the Attention Network Task (ANT; Fan, McCandliss, Sommer, Raz, and Posner 2002), a variation on the classic flanker response time task (Eriksen 1995; Eriksen and Eriksen 1974). The ANT uses combinations of alerting

cues, spatial cues, and flanker interference to separately assess alerting, orienting, and executive control networks, respectively. Pairing the ANT with a walking task that varied in difficulty would enable a precise analysis of the dynamics of attention control during walking.

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